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Particle sieve analysis for determining solids removal efficiency of water treatment components in a recirculating aquaculture system

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ABSTRACT

Recirculating aquaculture systems offer potential finfish production units for small-scale entities as well as large-scale operations. However, the water treatment components of such systems require efficient and proper operation to assure successful production. This study evaluated the solids removal ability of three water treatment components in a two-tank recirculating aquaculture system (28 m^3) utilized for the warmwater production of tilapia. The components include a swirl separator, a floating plastic bead bioclarifier, and a fluidized sand filter. Sampling was conducted at five different points in the system with each sample volume being serially fractionated through sieves in size ranging from 23 to 500 μm. Total suspended solids analysis was completed on each sample set to determine the particle size distribution of the influent and effluent water and removal efficiency of each component. The removal efficiency of the swirl separator was over 90% for particles larger than 250 μm and the propeller-wash bead filter had removal efficiencies greater than 85% for particles larger than 55 μm. The fluidized sand filter had the best removal for the smaller size particles with over 65% removal efficiency for particles between 23 and 55 μm. The overall reduction in total suspended solids for the treatment loop of the three components of this small-scale experimental unit was over 85% and adequately removed the suspended solids from the recirculating water for tilapia growout production.

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1. Introduction

Aquaculture has become a necessity to meet the demand for foodfish and increasingly contributes towards total world foodfish production (Bai, 2007). Recirculating aquaculture systems (RAS) offers an alternative means of fish production for areas with limited land availability for traditional pond fish. A RAS operating at peak efficiency is capable of supporting very high densities of fish, up to 100 kg of fish per m^3 of system volume. With recirculating finfish systems operating at intensive culture densities it is important to have the proper water treatment components to handle solids removal, biofiltration, oxygenation, and degasification. The design and efficiency of these components is paramount and it essential that all these components function properly to assure successful and efficient foodfish production.

Management and removal of solids is one key process in an RAS. In recirculating finfish systems the main particulate waste materials are feces, uneaten feed, decaying fish, and tank and pipe biofilm slough (Chen et al., 1993; Patterson and Watts, 2003). Solids that are not removed from the RAS have numerous consequences for the fish in the system and system components. The presence of suspended solids in recirculating finfish aquaculture systems can cause damage to fish gills, increase biochemical oxygen demand, reduce biofilter nitrification, and increase ammonia in the system (Chapman et al., 1987; Bergheim et al., 1998; Wong, 2001; Zhu and Chen, 2001). The solids found in RAS operations vary in size and settling properties and have an effect in the design and operation of the solid removal mechanisms (Merino et al., 2007). The objective of this study was to characterize the particle size removal of key treatment devices in a warmwater RAS for tilapia culture. The components include a swirl separator, a propeller-wash bead filter, and a fluidized sand filter.

2. Materials and methods

The water treatment components characterized for particle solids removal were utilized in a recirculating finfish aquaculture system located in the aquaculture park of Harbor Branch

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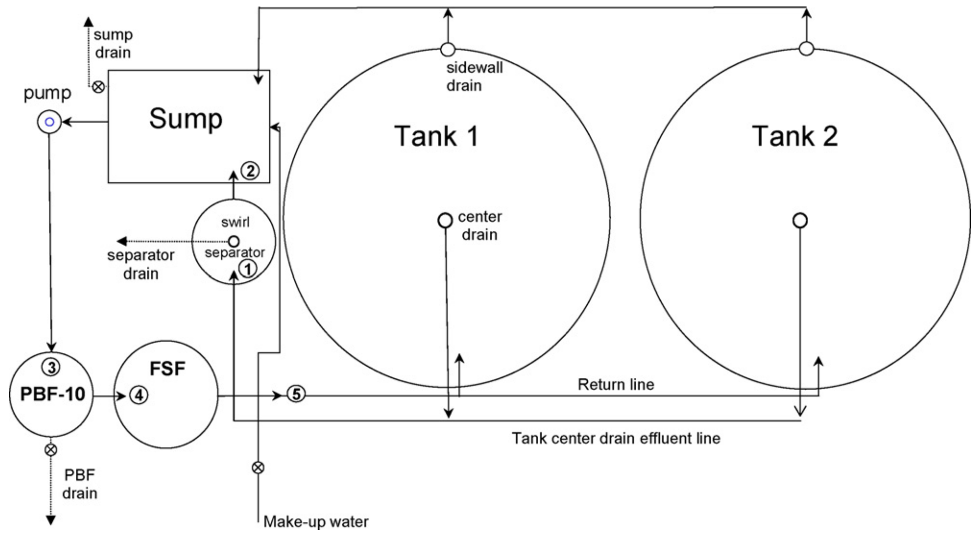

Fig. 1. Schematic of the recirculating aquaculture system with the two 12.5 m^3 culture tanks, 0.6 m^3 swirl separator, 0.7 m^3 sump, 0.28 m^3 propeller-wash bead filter (PBF), and the fluidized bed sand filter (FSF). System volume of 28 m^3 and a tank turnover time of approximately 80 min. The five sampling stations for component particle analysis are located by the circled numbers 1–5.

Oceanographic Institute, Florida Atlantic University, Fort Pierce, FL. The finfish RAS in this study consisted of two 3.65 m diameter panel fiberglass tanks with a sloped bottom. Tank culture volume was approximately 12.5 m^3 and each tank was operated in a dual drain design mode with a center bottom drain (5 cm in diameter) and a sidewall drain (10.2 cm in diameter). The center bottom drain of the tanks provided low volume–high solids effluent flow to the 0.6 m^3 swirl separator (W. Lim Corporation, San Diego, CA). Effluent flow was approximately ten percent of the system return water flow out of the tanks and measured by a simple volumetric technique (bucket and stopwatch). The swirl separator was purged daily (approximately 25 L) and emptied weekly for sidewall cleaning. Flow from the outflow of the swirl separator joined the high volume–low solids flow from the elevated sidewall drain (approximately 0.76 m from the tank bottom) into the system sump (0.7 m^3). Water from the sump was pumped to a 0.28 m^3 propeller-wash bead beadfilter (Aquaculture Systems Technology, New Orleans, LA) at a flow rate of approximately 340 Lpm. Water flow was measured by a portable ultrasonic flowmeter (Greyline Portaflow, Massena, NY). Backwashing of the bead filter was an automated process activated daily. Additional solids removal and biofiltration was provided by a fluidized sand filter (Model FBB-100HR, Aquaneering Inc., San Diego, CA). The diameter of the sand filter vessel was 1.07 m and 2.6 m in height with a calculated volume of 2.35 m^3. The filter was filled with 1510 kg of silica sand (0.92 m^3) that had a D_{50} of 0.37 mm and a uniformity coefficient of 3.1. The flow distribution mechanism of the fluidized bed sand filter was a vertical pipe manifold system (Weaver, 1991). The pipe manifold originates at the top of the vessel and then distributes water flow into vertical pipes that extend down to the base of the sand bed. Water flow from each vertical pipe is uniformly distributed into the sand without a gravel layer. As the water is uplifted through the sand bed, the sand is fluidized and the sand bed expanded sufficiently to prevent large sand particles from settling on the bottom of the filter. The expansion of the sand bed was maintained at approximately 60%. From the fluidized sand filter water gravity flowed back to the culture tanks in a 10.2 cm diameter pvc pipe and entered each tank through a slotted 5.1 cm diameter pipe. Water flow into each tank was controlled by a manual ball valve. All pvc fittings and pipe were Schedule 40. Tank aeration was provided by four 1.5 m bioweave diffuser hoses (Aquatic Eco-Systems, Apopka, FL) placed around the tank perimeter and supplied by the facility 5 kW regenerative air blower (Sweetwater, Aquatic Eco-Systems, Apopka, FL). The schematic of the system is provided in Fig. 1.

Each tank was stocked with tilapia GMT juveniles (*Oreochromis niloticus*) for a growout production strategy. The number and weight of fish in each tank was estimated from a sub-sample of 60 fish from each tank. The estimated number of fish in tank 1 was 3400 with a total biomass of 358 kg. The average weight of the fish in this tank during the study was approximately 105.3 g. The estimated number of fish in tank 2 was 880 with a total biomass of 172.4 kg and an average fish weight of 196 g. The feed provided was a floating pellet (3.1 mm) with a 32% crude protein content. Tanks were provided with approximately 4.5 kg of feed a day, divided into three feeding periods (0800, 1200, and 1800). Per feed event, tank 1 received 1050 g and tank 2 received 450 g of feed. The 1200 and 1800 feedings were provided by automated feeders (Sweeney Feeders, Boerne, TX).

Solids sampling was conducted at five different locations for the three different solids capture devices employed in the recirculating aquaculture system. Sampling was conducted 2–3 h after back-washing of the propeller-wash bead filter. Samples were drawn into two buckets of 15 L each and combined to provide a total sample volume of 30 L. The inflow sample of the swirl separator (location 1) was collected by placing a silicon tube (1.9 cm inside diameter) in the swirl separator inflow. The outflow sample of the swirl separator (location 2) was collected at the outflow port with the 15 L buckets. The inflow sample of the bead filter (location 3) was collected from a sample port at the filter inlet that was fitted with a 1.3 cm diameter labcock valve. The outflow sample of the bead filter, which also served as the inflow sample of the fluidized sand filter, was collected from the sample port (location 4) at the outflow of the bead filter. The outflow sample for the fluidized sand filter was collected from the surface water above the fluidized sand bed (location 5). Sample locations are indicated in Fig. 1. The valves and siphon tube were allowed to run freely for 15–30 s before collecting the sample volume to get rid of any waste material that was a result of flow disturbance or had accumulated in the interior of the valve or pipe walls. The collected samples were immediately processed through a series of five sieves with varying mesh size for total suspended solids (TSS) analysis.

The sieves were constructed specifically for this experiment. The sieves were constructed using Schedule 40 pvc pipe (20.3 cm in diameter and 10.2 cm in height) and nytex screen material

Fig. 2. Image of the particle sieve (500 μm) that was constructed for this experiment. The sieves were constructed using Schedule 40 pvc piping (20.3 cm in diameter and 10.2 cm in height) and nytex screen material. The screens were attached to the bottom of the pvc pipe with a two part epoxy. The mesh sizes of the nytex screen were 500, 250, 105, 55, and 23 μm.

(Fig. 2). The screens were attached to the bottom of the pvc pipe with a two part epoxy. The screen mesh sizes were 500, 250, 105, 55, and 23 μm. Each 30 L sample was serially fractioned through the screens. Collected solids were rinsed from the screens with distilled water and stored in 0.5 L plastic sample bottles and stored at 4 °C until TSS analysis was initiated. TSS analysis was conducted using Standard Method 2540-D (APHA, 1997). TSS analysis was completed within 5 days of each sample collection date. Before analysis the glass fiber filters (Whatman GF/C) were pre-rinsed to remove any possible particulates and each sample was sufficiently homogenized before filtering. Sample volumes used for TSS analysis ranged from 35 to 200 mL and samples were done in triplicate. Final TSS calculations for each serial particle fraction were determined using a sample volume equal to 30 L. The percent removal efficiency for each solids capture device for each particle size category was computed using the equation below:

$$\text{RE}\,(\%) = \left[\frac{S_{\text{In}} - S_{\text{Out}}}{S_{\text{In}}}\right] \times 100$$

where RE: removal efficiency (%), S_{In}: mean TSS concentration of inlet sample for the specific screen mesh size (mg/L) and S_{Out}: mean TSS concentration of outlet sample for the specific screen mesh size (mg/L).

Sample collection from each of the three devices inflow and outflow was conducted weekly for 3 weeks and the data is reported as a mean of the three sample collections. System operational and feeding regimes remained unchanged during the sample collection period to assure steady state operation of system components.

3. Results

The water flow rate through the swirl separator was 40 Lpm providing a hydraulic retention time of approximately 15 min for particle settling resulting in a considerable portion of the large particles to be removed. The average TSS of the separator inflow was 9.25 ± 5.31 mg/L and the average TSS of the separator outflow was 2.87 ± 1.08 mg/L. The average removal efficiency for suspended solids removal through the swirl separator was 65.6%. The mean particle size distribution in and out of the swirl separator for three single-pass sampling events is presented in Fig. 3a.

The influent water into the swirls separator from the tanks had a majority of particles in the 105–250 and 250–500 μm size range, 26.3 and 28.3%, respectively. The percent of particles larger than 500 μm was 17.2% and total percent of particles less than 100 μm was 28.3%, with less than 1% of these particles being under 23 μm. In the separator effluent flow less than 10% of the particles were greater than 250 μm and the distribution of particle increased in the other size range categories. Distribution of particles in the 105–250 μm group increased to 36.3%, the 55–105 μm increased to 25.8%, and the 23–55 μm group increased to 27.2%, respectively. The swirl separator demonstrated greater than 90% removal efficiency for particles larger than 250 μm, and over 50% removal efficiency for particles in the 105–250 μm size category (Fig. 3b). For the particles between 23 and 105 μm, removal efficiency was in the range of 15 and 30%. In one sample set, the particle concentration in the <23 μm category of the separator effluent was twice the influent concentration (0.08 mg/L versus 0.04 mg/L) resulting in a negative removal efficiency for this category (−19.4%). The removal efficiencies for the other two sample sets in this size category (<23 μm) was 16.7 and 25.0%, respectively.

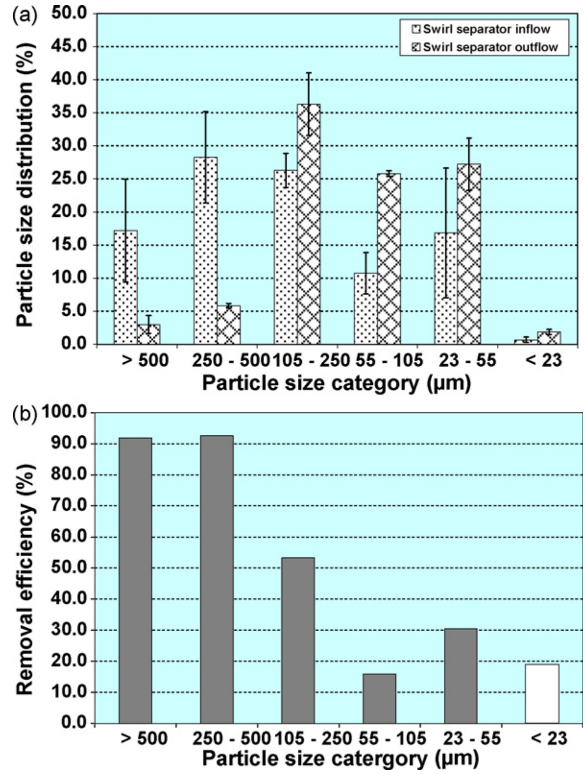

Fig. 3. (a) Particle size distribution of the inflow and outflow water from the 0.6 m^3 swirl separator utilized in a warmwater recirculating aquaculture system for tilapia culture and (b) removal efficiency of suspended solid particles by the 0.6 m^3 swirl separator utilized in a warm water recirculating aquaculture system for tilapia culture (note: in the <23 μm particles size category the removal efficiency was negative indicating an increase in the concentration (mg/L) of particles in that category. The increase in particle concentration for this size category was approximately 19.4%).

The propeller-wash bead filter in the system was operated as a mechanical filtration component although the manufacturer advocates its duel use for clarification and biofiltration. The hydraulic loading rate on the bead filter during the experimental period was approximately 0.91 Lpm/m^2 of filter media with a feed loading rate of approximately 16 kg of feed/m^3 of media. The average TSS of the water inflow of the bead filter (after the sump) was 6.63 ± 0.44 mg/L and the average TSS value of the bead filter outflow was 1.78 ± 0.08 mg/L for an average removal efficiency of 73.1%. The mean particle size distribution of the water in and out of the bead filter for three single-pass sampling events is presented in Fig. 4a. Particle size of the incoming water to the bead filter was well

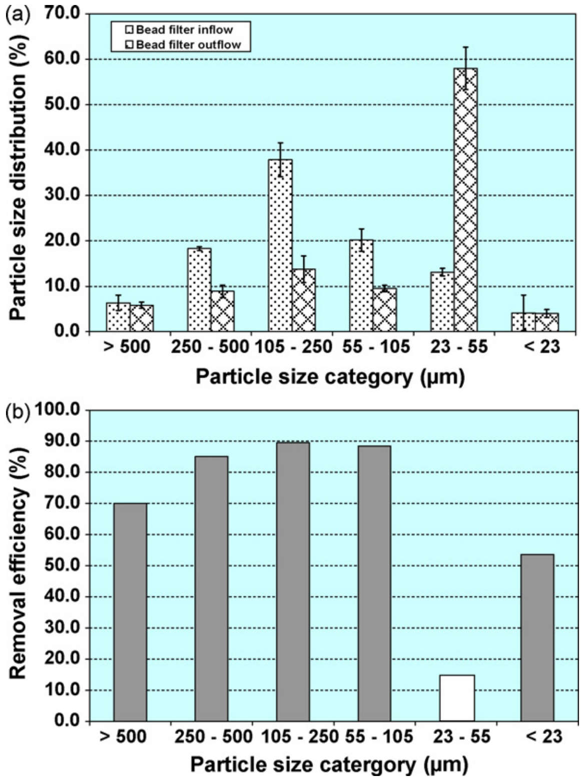

Fig. 4. (a) Particle size distribution of the inflow and outflow water from the 0.28 m^3 propeller-wash bead filter utilized in a warmwater recirculating aquaculture system for tilapia culture and (b) removal efficiency of suspended solid particle by the 0.28 m^3 propeller-wash bead filter utilized in a warmwater recirculating aquaculture system for tilapia culture (note: in the 23–55 particles size category the removal efficiency was negative indicating an increase in the concentration (mg/L) of particles in that category. The increase in particle concentration for this size category was approximately 13.4%).

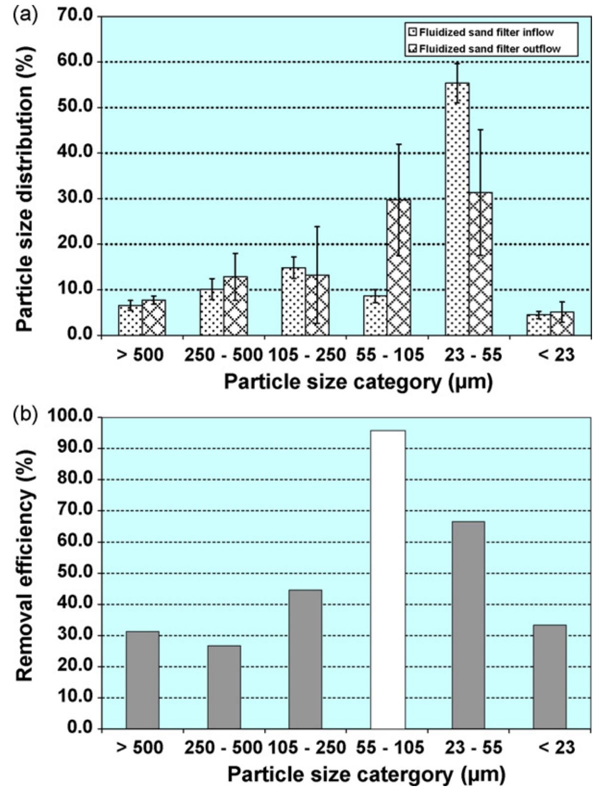

Fig. 5. (a) Particle size distribution of the inflow and outflow water from a fluidized sand filter utilized in a warmwater recirculating aquaculture system for tilapia culture and (b) removal efficiency of the suspended solid particles by the fluidized sand filter utilized in a warm water recirculating aquaculture system for tilapia culture (note: in the 55–105 particles size category the removal efficiency was negative indicating an increase in the concentration (mg/L) of particles in this category. The increase in particle concentration was approximately 95%).

distributed. Over 30% of the particles were in the 105–250 μm range, 4.2% of the particles were less than 23 μm, 6.4% of the particles were greater than 500 μm, and 13.1–18.3% of the particles were in the 23–55 μm and 105–250 μm category, respectively. For the outflow water of the bead filter there was an increase in the distribution of particles in the 23–55 μm range, a decrease in distribution for particle categories larger than 55 μm and less than 500 μm. There was no significant change in the distribution of particles <23 and >500 μm. The relative removal efficiency of suspended solids for particles greater than 55 μm ranged between 70 and 90%. There was a 13.4% increase in the concentration of particles in the 23–55 μm category, and roughly a 50% removal of particles that were <23 μm (Fig. 4b).

The fluidized sand filter was the final filtration component of the water treatment process in the recirculating aquaculture system. The fluidized sand filter was employed mainly for its biofiltration capacity rather than as a solids removal device in this RAS configuration. The data for the distribution of particles in the bead filter outflow also served as the particle size distribution of the inflow water for the fluidized sand filter. The TSS concentration of particles into the fluidized sand filter was 1.78 ± 0.08 mg/L (same as the bead filter outflow) and the outflow TSS concentration was 1.05 ± 0.11 mg/L for an average removal efficiency of 41.4%. The distribution of particles for the fluidized sand filter inflow and outflow water either increased or remained the same for all the size categories except the 23–55 μm category which decreased from 55.3 to 31.4% (Fig. 5a). The distribution of particles in the 55–105 μm size increased the most between filter inflow and outflow, going from 8.6% of the particle distribution for the filter influent water flow to 29.7% of the particle distribution on the filter outflow. The fluidized sand filter was only above 50% relative efficiency for particle removal in the 23–55 μm category (actual value of 66.5%) (Fig. 5b). Similarly, as in the bead filter, there was an increase in TSS concentration for one particle size category, the 55–105 μm size category. The concentration of particles in this size category increased from 0.15 ± 0.04 mg/L in the inflow to 0.40 ± 0.21 mg/L for the outflow resulting in a negative removal efficiency of 95.8%.

4. Discussion

Suspended solids adversely impact all aspects of a recirculating system and a successful performance criteria of any water treatment scheme in a recirculating system is the removal of solid wastes (Timmons and Ebeling, 2007). Various solids removal strategies are used in recirculating aquaculture systems (Huguenin and Colt, 1989; Lawson, 1995) and this paper focused on the swirl separator, propeller-wash bead filter, and a fluidized sand filter. Simple design and operational changes could potentially improve the particle removal efficiency of the swirl separator. Davidson and Summerfelt (2005) concluded that a radial flow settler design is twice as efficient in TSS removal as a swirl separator of similar size and surface loading. Veerapen et al. (2005) reported solid removal performance in separators is mainly due to gravity rather than centrifugal forces and separation is mainly by sedimentation. The basic separator design is a cylindrical tank with a conical base. The flow into the separator is tangential and a swirling flow in the tank is generated. In general, separators are operated with no continuous underflow but opened intermittently to purge out the settled solids. The undertow contains most of the solid waste and the overflow, consisting mainly of clear water, exited at the top through a side outlet. The separator design and operation in this RAS was similarly operated with a 10.2 cm side outlet and a daily purge from the cone bottom of the captured settled solids. The removal efficiency of this unit process was over 90% for particles greater than 250 μm and removal efficiency of the smaller, lower specific weight particles were much lower, 50% and under. Basically, separators (or hydrocyclones) are commonly used in the wastewater treatment industry to remove high specific gravity particles (i.e., sand and grit) that have a specific gravity 2.5 times greater than water (Paul et al., 1991).

Simple design and operational changes could potentially improve the particle removal efficiency of this unit. It was observed that too great of a tangential flow in the separator would shear biofilm particles from the side wall and raft into the outflow water. The separator also required periodic scrubbing of the sidewall to limit biofloc growth which would over develop and floc off the sidewalls and raft into the outflowing water. Following the study a 2.5 cm thick matala mat was placed on top of the surface overflow water which captured most of the rafting floc and larger sheared particles that were previously entering the sump.

Several types of mechanical filters such as microscreen filters, bag and cartridge filters, porous and granular media filters, and plastic bead media filters have been developed and utilized in recirculating aquaculture systems for effectively removing solid particles. Comparatively they all have advantages or disadvantages when considering head loss, filtration rates, filter run times, and ease of backwashing or cleaning. Optimization of particle removal in filters depends on the characteristics of the media (shape, size, surface and roughness), the removal mechanism employed, and the presence of biofilm on the media (Ahmed, 1996; Visvanathan et al., 1996; Mann and Stephenson, 1997). Results from this study have indicated 70 to 90% removal efficiency of the propeller-wash bead filter for particles greater than 55 μm, over 50% removal efficiency for particles less than 23 μm, and an increase in particle concentration in the 23–55 μm size category. Deshpande et al. (2004) observed approximately 20% removal efficiency of 5–10 μm particles and roughly 60% removal efficiency of 20–50 μm particles of similar bead filter media (standard cylindrical plastic polyethylene beads 3 mm in diameter) using test column filters (1.83 m in height and 2.54 cm in diameter) with 0.02 m^3 of media, a flow rate of 58.7 m^3/m^2 of media-day, and Arizona Test Powder (Burnsville, MN) as the solids material. Particle counts were conducted using a Beckman Coulter® Z Series™ particle and size analyzer (Fullerton, CA) on influent and effluent samples.

The increase (13.4%) in particle concentration for the size category 23–55 μm is peculiar. Basically, in a bead filter particles are captured by four mechanisms: straining, settling, interception, and adsorption, with backwashing operations having an impact on these processes. As time from the backwash increases, the interstial space (porosity) between the bead media becomes clogged with solids by the above four capture mechanisms. As the interstial space becomes clogged, particle removal efficiency increases for the smaller particles. Perhaps, the proximity of the study's particle sampling event to filter backwashing was too close and the interstial space of the media was not sufficiently clogged with particles to allow adequate capture of the particles in the 23–55 μm size category. Retrospection would suggest sampling at various time periods after the filter backflush event to provide a better representation of the filter's particle removal efficiency. Another possibility for the particle increase concentration would be the centrifugal impeller pump was breaking up the larger particles from the sump into moderately smaller particles prior to entering the bead filter. Although the pumping effect of particle size distribution was not investigated here, a study on the pumping effect on particles sizes in a recirculating aquaculture system for hybrid striped bass culture (*Morone saxatilis* $\times$ *M. chrsysops*) suggests that larger particles are broken into smaller particles by the centrifugal pumps and resulting an increase of smaller particle volume (McMillan et al., 2003).

Fluidized sand filters have been widely adopted in recirculating aquaculture systems for removing dissolved waste materials and maintaining excellent water quality for a variety of cool and warmwater fish species (Summerfelt, 2006). In typical RAS designs, fluidized sand filters are used for total ammonia and nitrite–nitrogen removal rather than removal of solids from the passing water flow. The cross-sectional area, bed depth, and size of sand utilized, water velocity, and bed expansion are some parameters that set the treatment capacity of the fluidized sand filter. In this study, the size and quantity of sand used in the filter was basically determined for its removal capacity of total ammonia and nitrite–nitrogen and expansion ability with the given water flow. Removal efficiency of solids was not the driving criteria of the treatment unit but data was collected for operational and future design purposes. As in the bead filter, an increase in particle concentration was observed for one category, the 55–105 μm size category (approximately 95%). The observed increased is believed to be a result of sloughed biofloc out of the top of the sand filter. The biofloc is the distinct layer of lightly biofilm coated sand particles that are at the top of the sand bed because of its lighter density. Usually the smaller sand sizes allow attachment of more biofilm and require harvesting or removal by siphoning to prevent the sand bed from overflowing at the filter outlet. It appears from the particle sieving results that these particles were actively being transported out of the filter and into the tanks during the sampling process. Sand particles were readily observed in the tanks where the water velocity was much slower and the scoured particle had lost is biofilm coating during transport into the tanks.

5. Conclusion

Paired *t*-test results indicated the solids concentration in and out of the three system components evaluated were statistically different ($P < 0.10$). However, system operational and configuration changes could contribute to improving the solids removal capabilities of the system. A simple mass balance analysis of the water flow and TSS concentration in and out of the sump indicates the water flow from the elevated sidewall drain was practically that of the swirl separator inflow concentration. Obviously, what was thought to be a high volume–low solids flow was not much different than the low volume–high solids flow going into the swirl separator. To improve the removal of settable solids from the center drain the bioweave tubing along the tank perimeter should be removed. It appears this method of in-tank aeration was resuspending the particles in the culture water and hindering settling and movement of the particles towards the center drain for removal. Addition of a pack-column tower after the sand filter could be implemented for aerating and degassing the return water. If the water is allowed to flow to the center of the tank unhindered by in-tank aeration this would lead to a greater tangential velocity at the center of the tank. A hydrodynamic study of multi-drain circular tanks by Despres and Couturier (2004) suggest that higher rotational velocities in circular tanks help carry solids to the central drain. However, too high of a velocity would create a center vortex that could lead to particle re-entrainment. A vortex breaker (standpipe with vertical fins) above the center drain would minimize the effects of the vortex and allow particles to fall into the center drain sump of a dual drain design. Based on the data from this manuscript the authors suggests removal of the in-tank bioweave aeration, daily purging of solids from the tank's center drain, directing flow from the elevated sidewall drains of the tanks through the swirl separator prior to entering the sump, and addition of a packed tower for water aeration and degassing.

The data and material presented provides field data to supplement existing published information regarding suspended solids removal for the swirl separator, propeller-wash bead filter, and fluidized sand filter. Overall, the swirl separator functioned well to remove the large particles over 250 μm, and the bead filter in removal of particles between 50 and 100 μm, with sufficiently smaller particle removal by the fluidized sand filter. Having established a base knowledge of the solids removal efficiency of these components for this system configuration and operation, additional data collection will continue to improve the management practices for optimally and cost effectively operating RAS components.

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